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Ultrasonic Motors (USM)
- An emerging actuation technology for planetary applications

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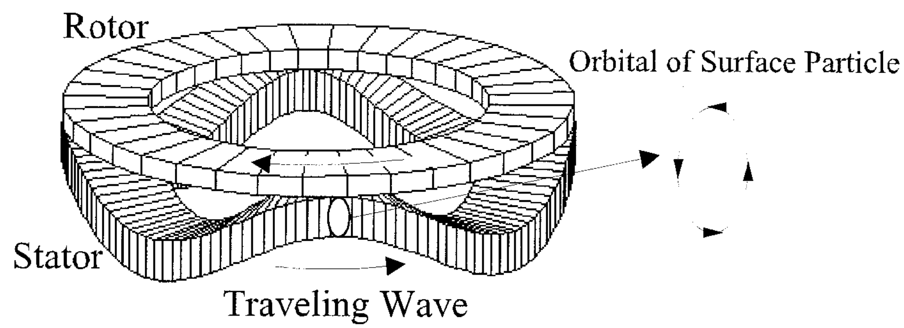
ULTRASONIC MOTORS (USM)

- Higher torque density
- Low speed - direct drive
- Self braking
- Easy position control
- Unique configurations: Pancake compact as well as annular shape for electronic packaging
- easy to miniaturize and to mass produce
- Not affected by magnetic field or radiation



Comparison between existing electromagnetic (EMM) motors and ultrasonic motors (USM)

Type	Description	Manuf.	Stall Torque (in. oz)	No-load Speed (rpm)	Mass (g)	Torque Density - without gear (Nm/kg)
EMM	DC, Brushless	Aeroflex	1.4	4.0K	256	0.04
EMM	DC Brush	Maxon	1.8	6.0K	38	0.45
EMM	AC, 3-phase	Astro	10.7	11.5K	340	0.21
USM	Traveling Wave- Disc	Panasonic	11	0.8K	70	1.10
USM	Stand. Wave - Rod Torsion	Kumada	189	0.12K	150	8.80
USM	Traveling wave- Disc	Shinsei	13	0.3K	33	2.70
USM	Traveling wave -Ring	Canon	17	0.08K	45	2.30

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Background

- Ultrasonic rotary motors were investigated as potential actuators of a robotic arm and end effector for planetary applications.
- The research effort was directed to develop USMs that can be operated at the harsh environment of Mars.
- A complete model of USM was developed coupling the
  1. 3D finite element model of the stator with piezoelectric elements
  2. Annular finite element model for the rotor
  3. Analytical model for the friction layer and the stator/rotor interaction
  4. Equivalent circuit for interface to electric driver
- USMS were installed onto a robotic arm and gripper and control issues were addressed to allow effective operation.

3D Finite Element

The discretized equation of motion of an elastic structure including piezoelectric materials can be expressed as

$$
\begin{aligned}
&[M]\{\ddot{\xi}\} + [C]\{\dot{\xi}\} + [K]\{\xi\} = [P]\{\varphi\} + \{F\} \\
&[P]^T\{\xi\} - [G]\{\varphi\} = \{Q\}
\end{aligned} \tag{1}
$$

For simple harmonic motion, we have

$$
\begin{aligned}
&([K] + j\omega[C] - \omega^2[M])\{\xi\} - [P]\{\varphi\} = \{F\} \\
&[P]^T\{\xi\} - [G]\{\varphi\} = \{Q\}
\end{aligned} \tag{2}
$$

and constraints as

$$
\begin{aligned}
&q_1 = q_2 = \ldots = 0 && \text{for nodes not on electrodes} \\
&\varphi_1 = \varphi_2 = \ldots = V_e && \text{for nodes on electrodes}
\end{aligned} \tag{3}
$$

where V_e is the voltage on electrode *e*.

Friction Layer and Stator/Rotor Interaction

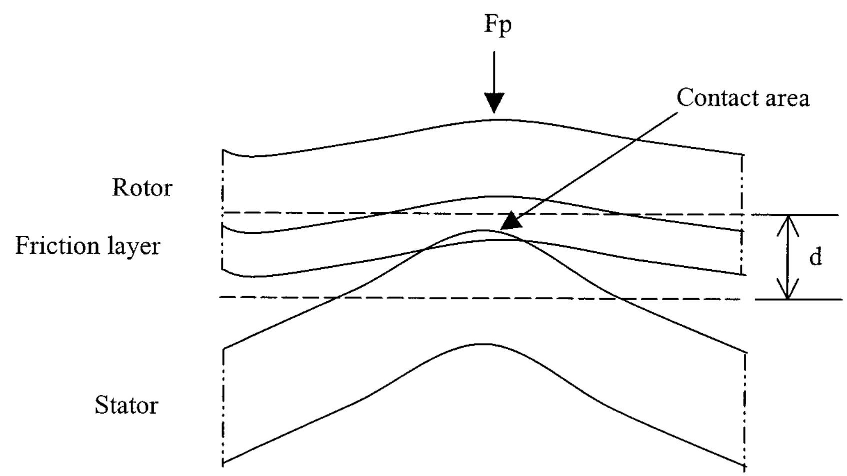
- Normal pressure: Friction layer as vertical springs in Z direction

$$p = \begin{cases} h_p E/h & h_p >= 0 \\ 0 & h_p < 0 \end{cases}$$

- Friction:

$$\tau = sign(v_s - v)\mu p$$

- Numerically solved the nonlinear equations to find the interaction force for given traveling wave on stator



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Equations of Traveling Mode

The stator:

$$(\omega_0^2 + j\omega R - \omega^2)u_1 = \frac{1}{2}p(V_1 + jV_2) + Fs_1$$

$$Q_1 = \frac{1}{2}p(u_1 + u_2) + C_0V_1$$

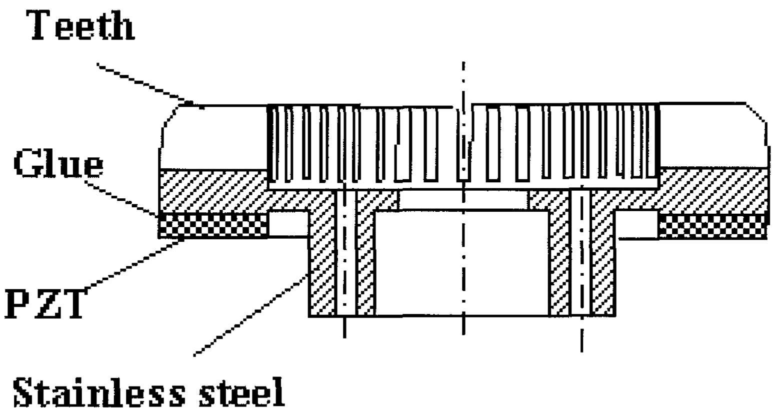
$$Fs_1 = -(\int w_s^* p dA + \int v_s^* \tau dA)$$

The rotor:

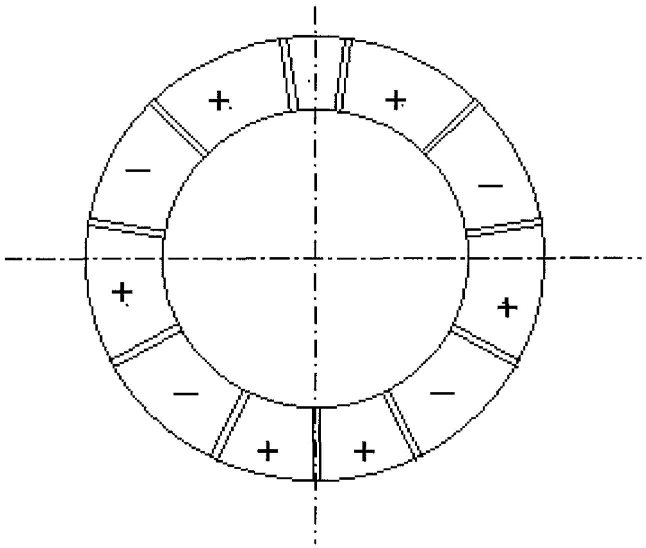
$$(\omega_{r0}^2 + j\omega R_r - \omega^2)u_{r1} = Fr_1$$

$$(\omega_{r0}^2 + j\omega R_r - \omega^2)u_{r1} = \int w_{r1} p dA$$

Piezoelectric Stator and PZT Ring



(a) Stator of piezoelectric motor



(b) PZT ring

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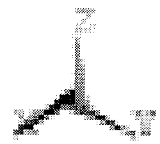
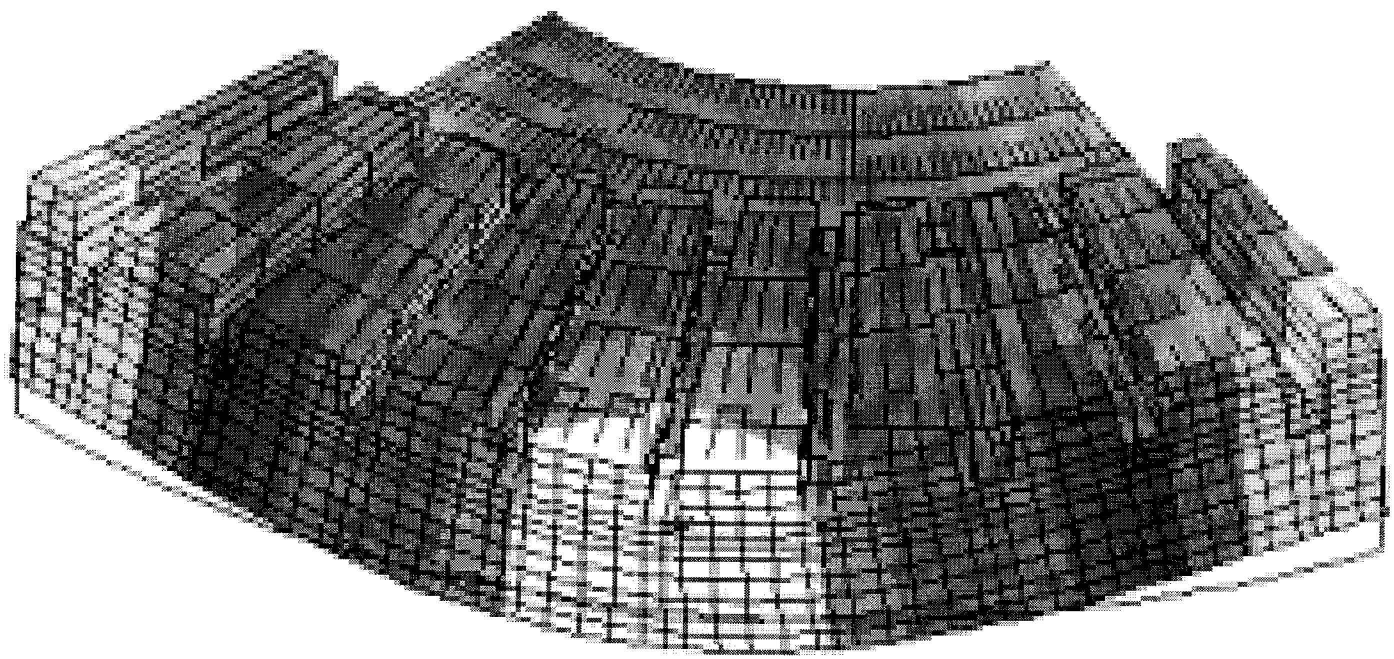
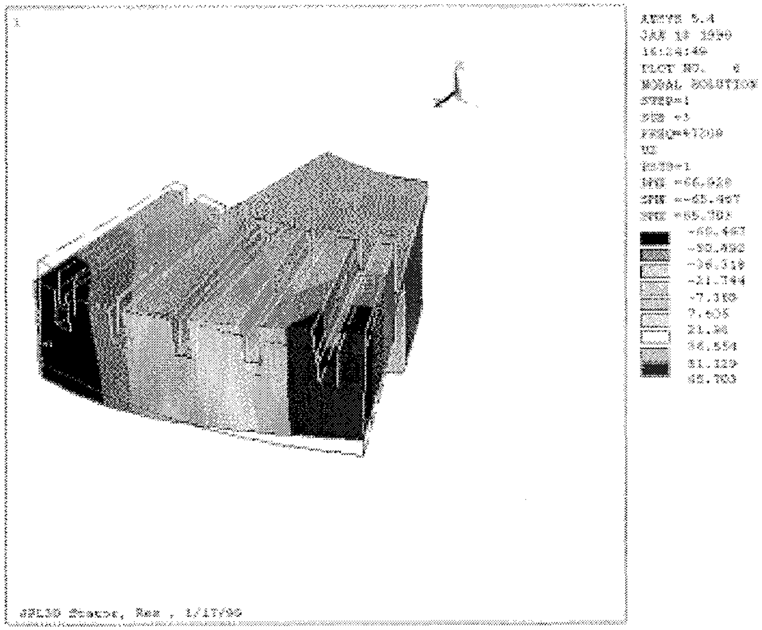
3-D FEM Analysis of USM Stators

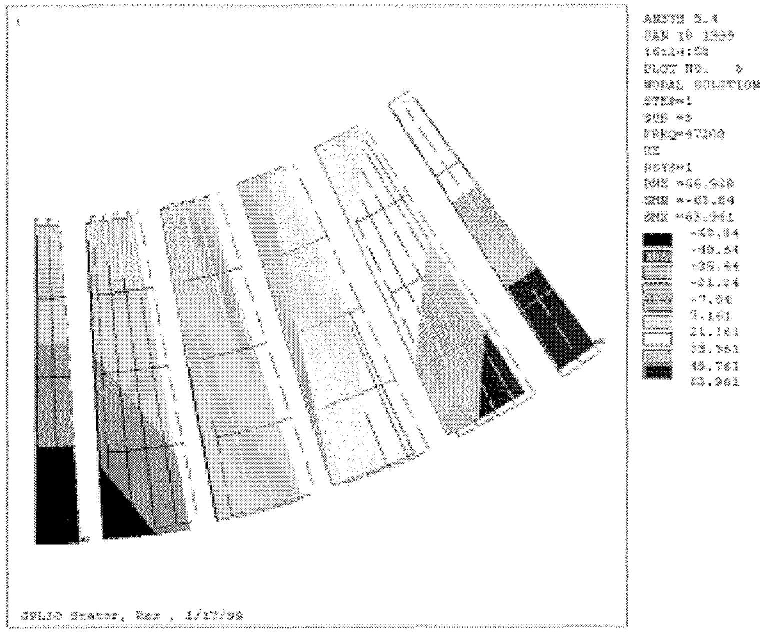
One wavelength segment (of 5 total in the specific design) of a USM stator is shown with the teeth and the overall flexural displacement. The displace is assisted with color graphic and it is part of an animation that was developed to view the motor performance interactively.



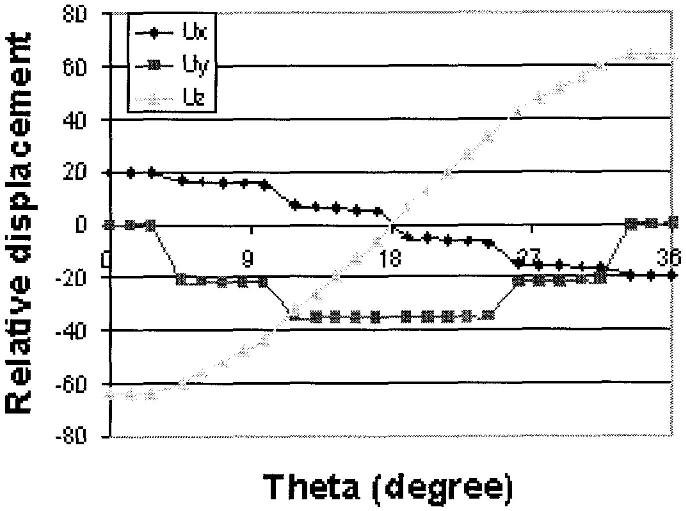


Detailed Modeling Using ANSYS FEM Analysis

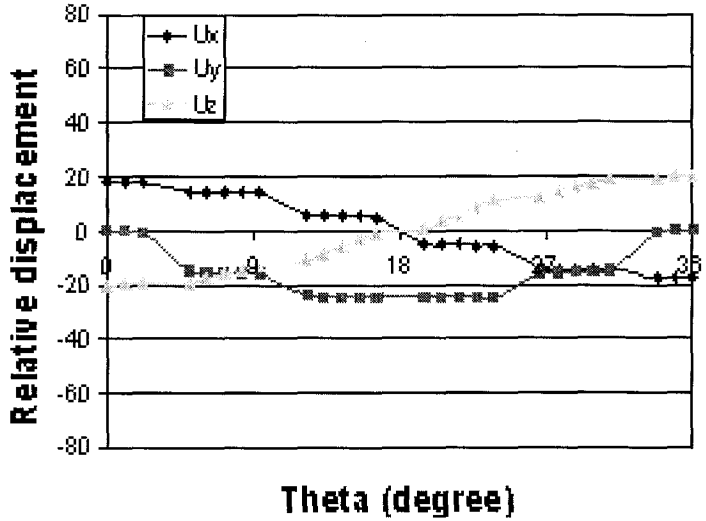




Distribution of the displacements on the top surface of the teeth



(a) At the outer diameter of the teeth

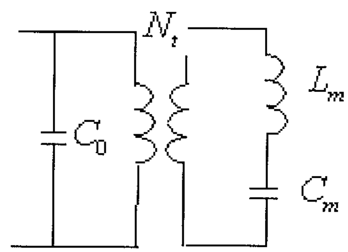


(b) At inner diameter of the teeth

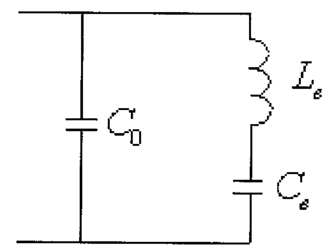
Equivalent Circuit

One terminal of full electrodes

The parameters are solved according to the Fs, Fp and Ct where are computer by 3D FE.



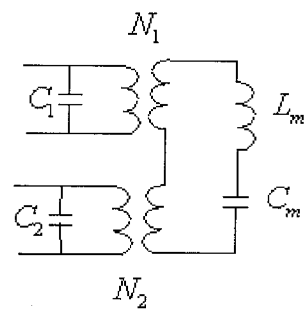
a. Electro-mechanical circuit with one terminal of full electrodes



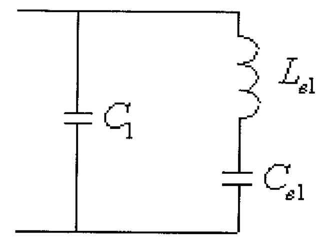
b. Electrical circuit

One terminal of partial electrodes

These parameters are converted from the full electrodes case

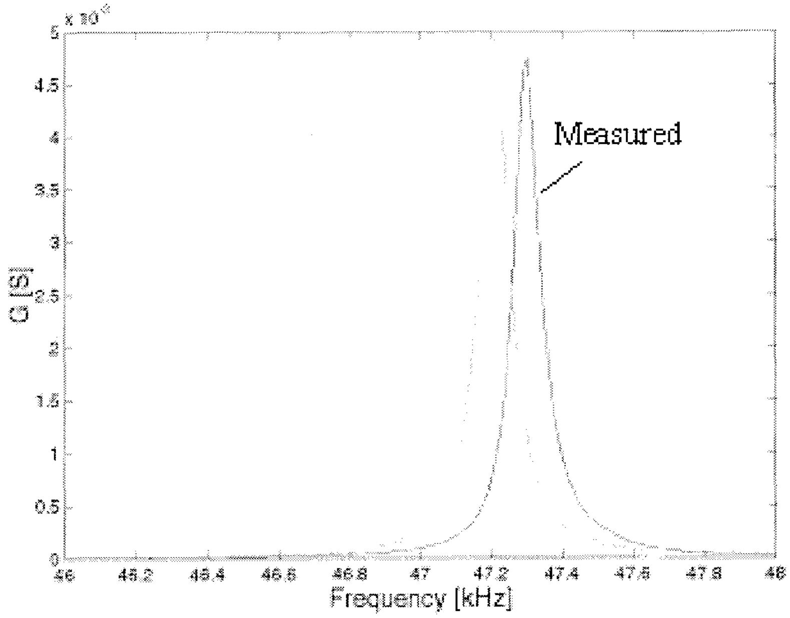


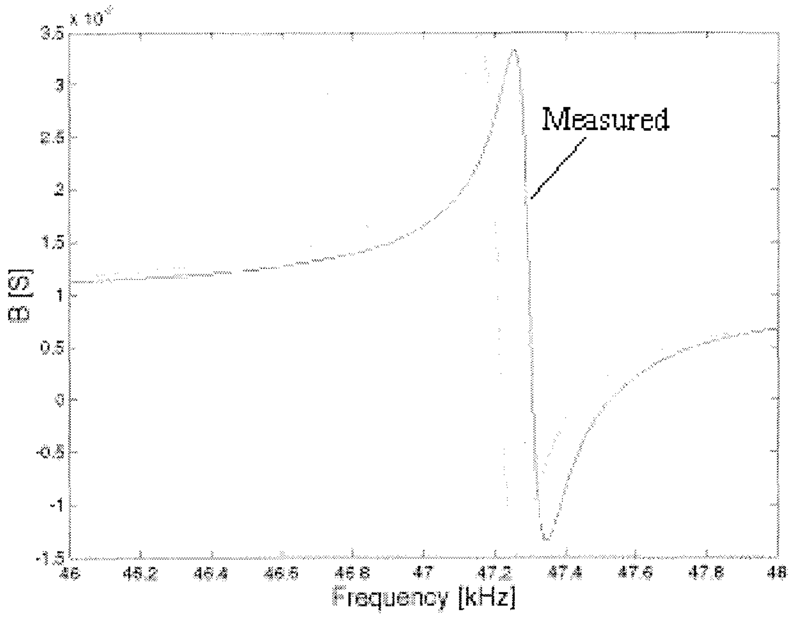
c. Electro-mechanical circuit with two terminals



d. Electrical circuit with one of two terminals used

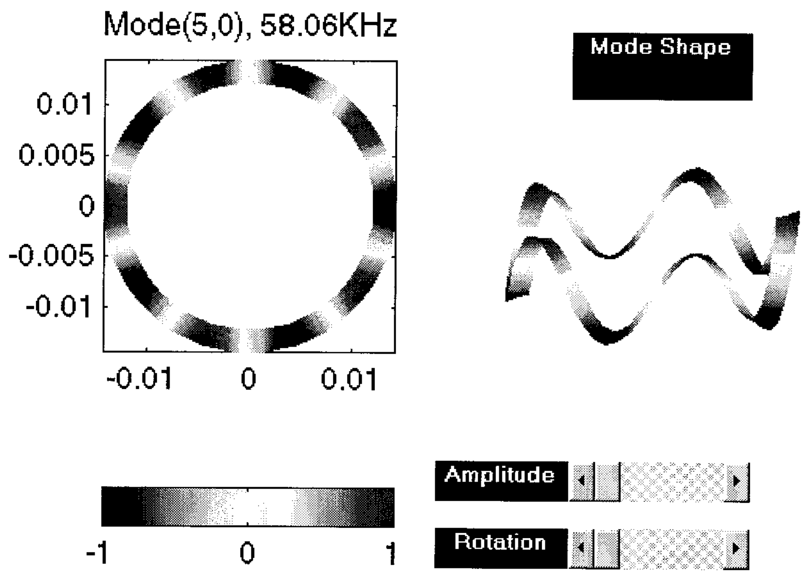
Computed Electric Admitance vesus Measured





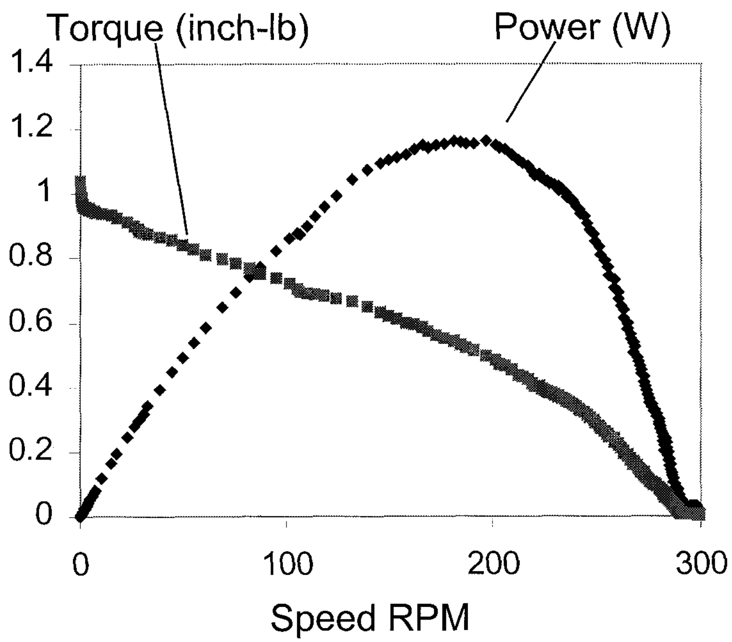
The Rotor

Annular finite element approach for the rotor

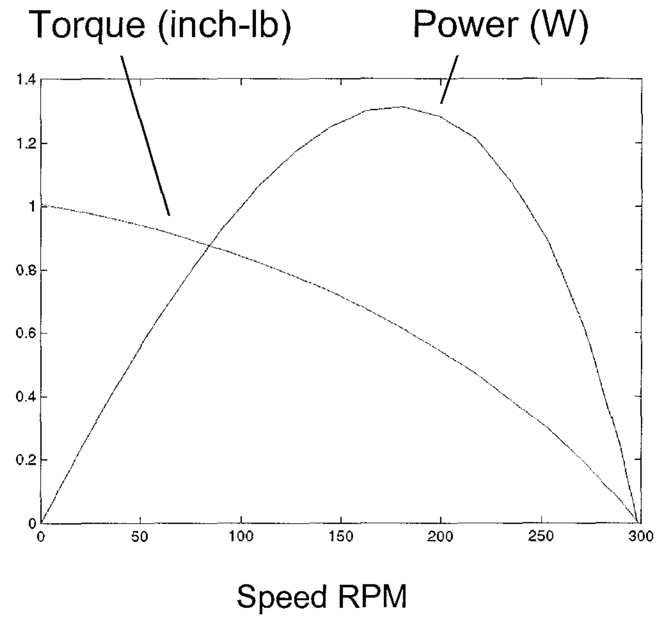


The frequency and mode shape of the mode (5, 0) of the rotor

Performance



A. Measured Motor Performance



B. Computed Motor Performance

Constant Amplitude Driving:

$A_z = 2.5\ \mu m$, $R = 1.3$ cm, $W = 2$ mm, $F = 60$ N, $\mu = 0.16$

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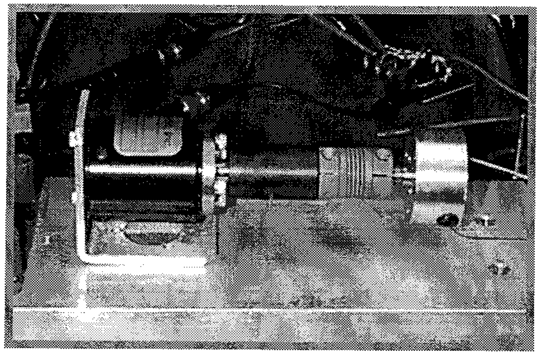
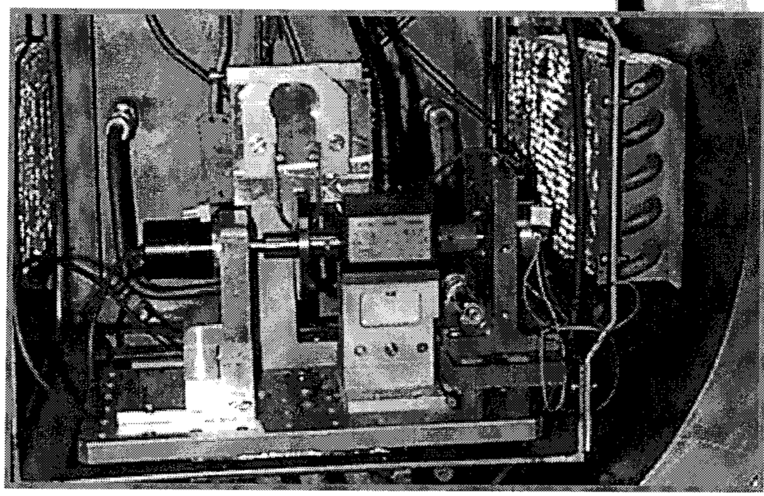
USM test facility

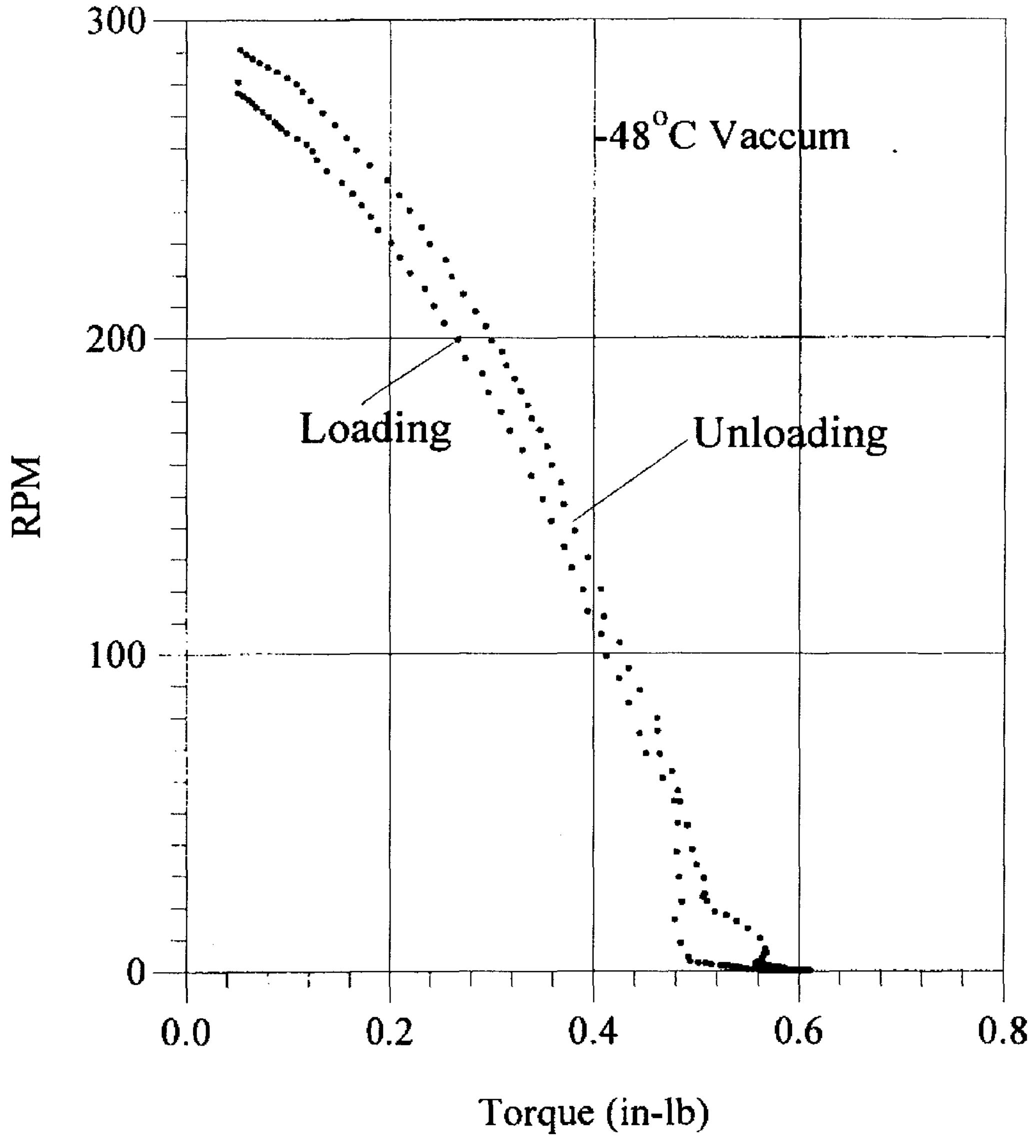


Stall-torque gauging



Torque-speed gauging

Cold-Start torque-speed curve for a 1.1-inch diameter USM at -48° C and $2x10^{-2}$ Torr.



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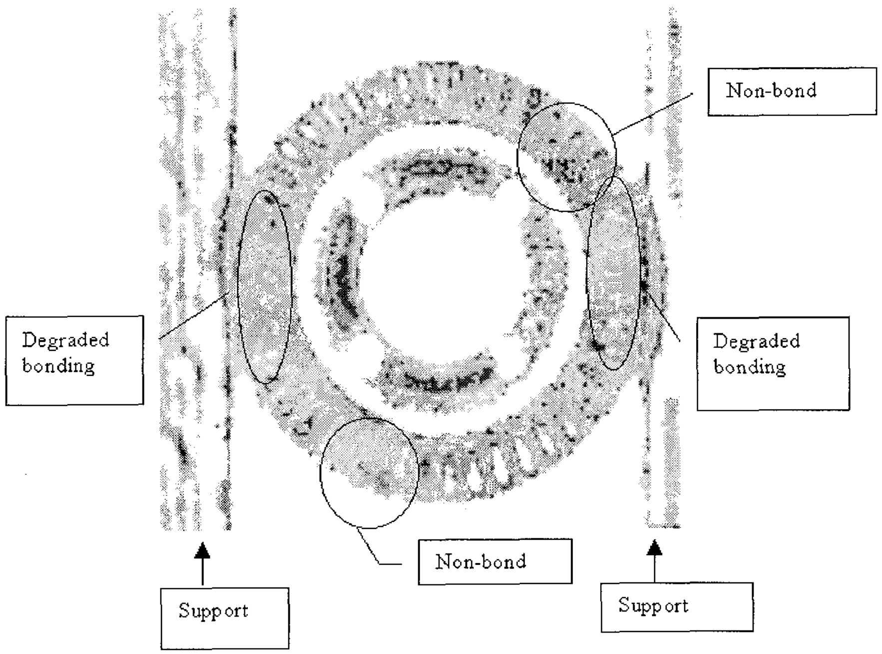
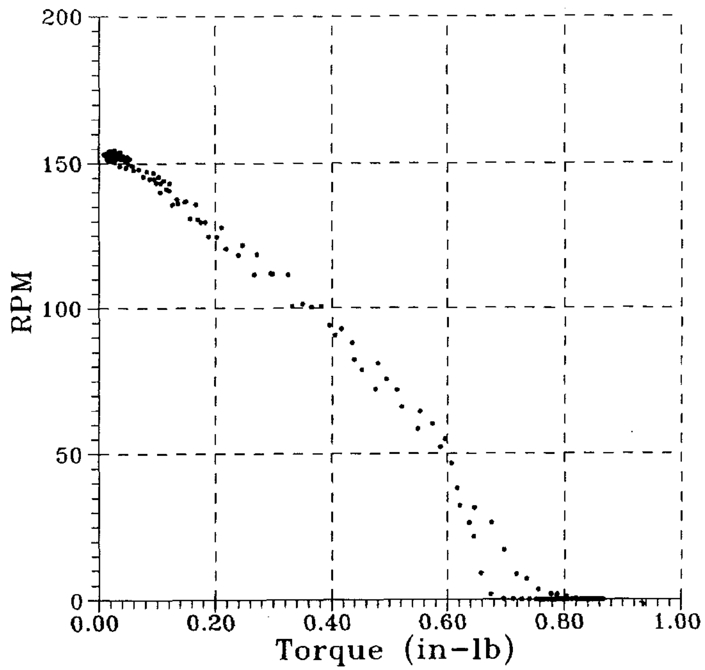
Cryovac response of USMs



An Ultrasonic C-Scan image of a 1.2" diameter stator (Shinsei) that was subjected to -150°C and 16 mTorr for over 67 hours.



Torque-speed performance of a JPL/QMI USM subjected to -150°C and 16 mTorr, lasted 336 hours

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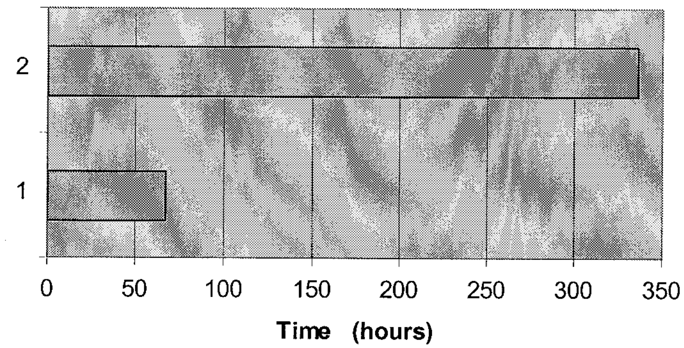
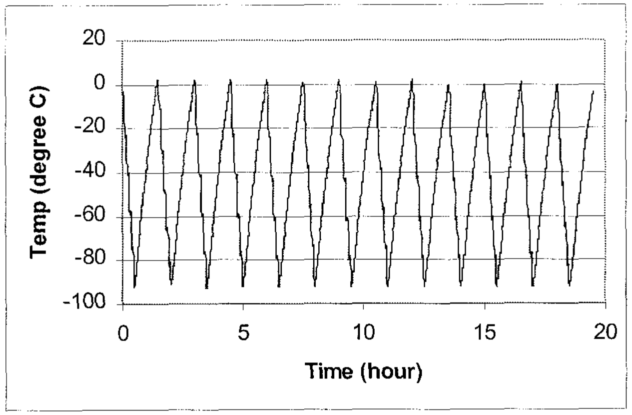
Lifetime of 1.2" diameter commercial and JPL/QMI USMs exposed to cryovac environment.

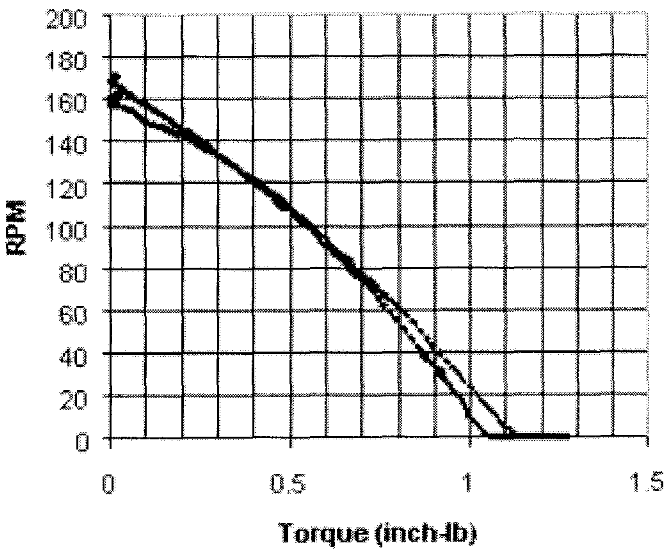


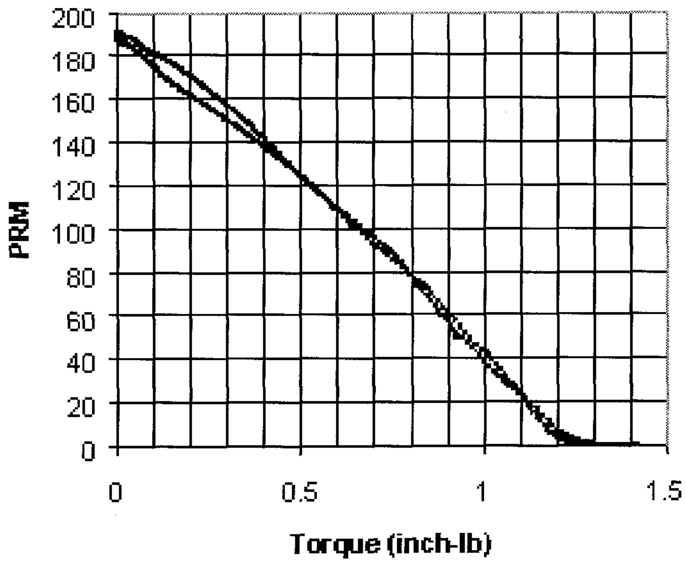
Notes:

- The commercial USM failed after 67 hours at -150° C and 16 mτ vacuum with 8 stall-torque tests.
- The JPL/QMI SRPD USM failed after 336 hours total of cryovac test (65 hour at –80° C and 25 mτ plus 271 hours at –150° C and 16 mτ). A slower operation was observed after about 210 hours, which may have been the result of a single segment failure (C-scan will be made in the near future). After about 8 hours from the beginning the motor had an electric wiring short which was fixed. The motor had 36 stall-torque tests.

Temperature Cyclic Test





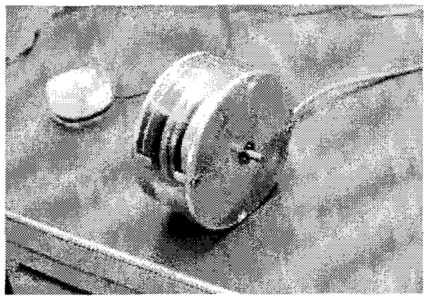


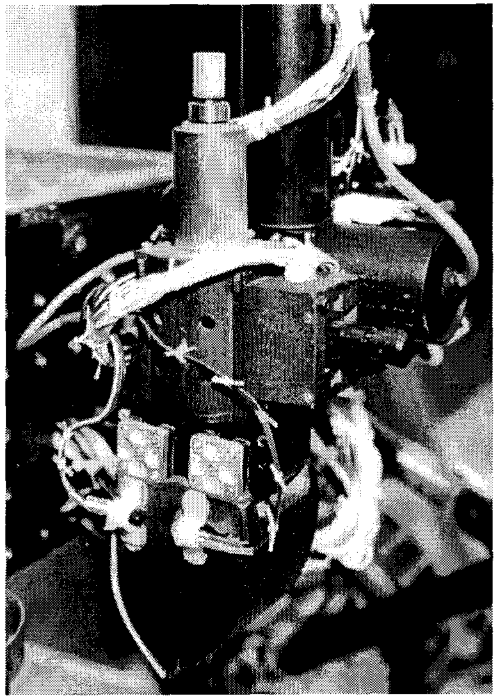
(a) Before test

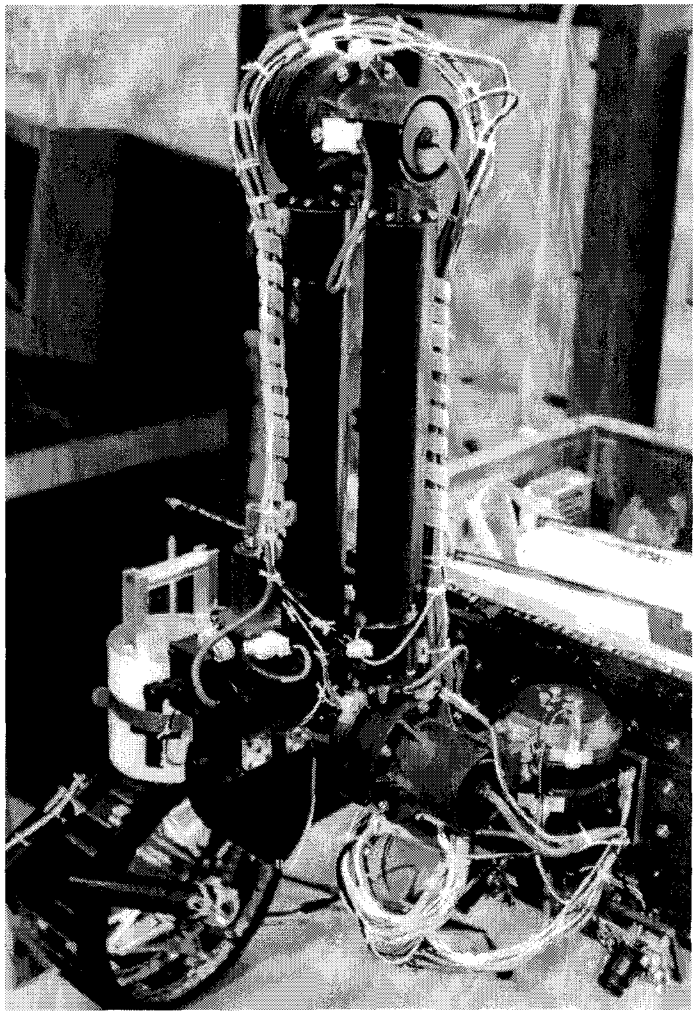
(b) After 231 temperature cycles

LSR Microarm-1 and gripper driven by USMs

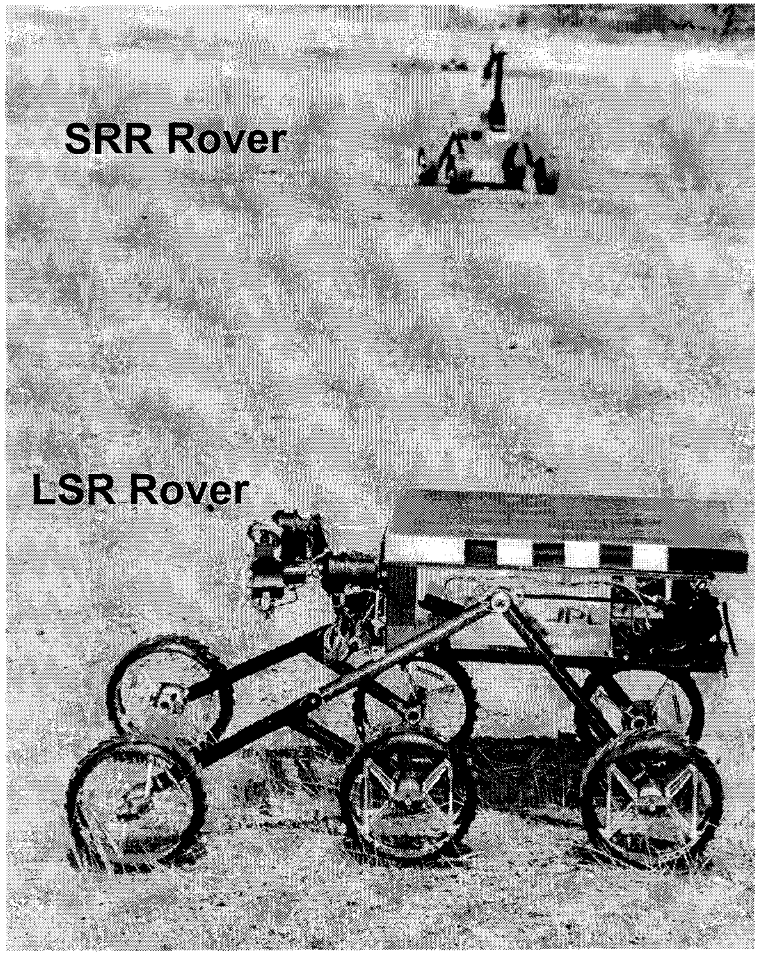
Photos available on:
http://robotics.jpl.nasa.gov/tasks/pdm/homepage.html



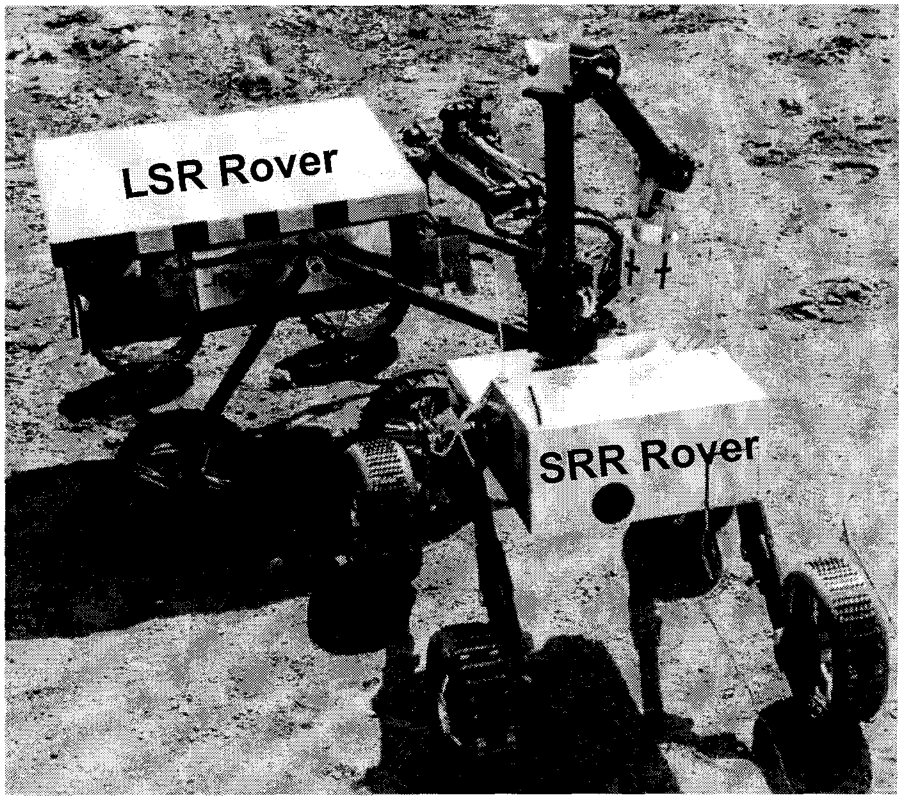




Microarm-1 on the LSR Rover driven by USMs



Sample transfer demonstration with MicroArm-I mounted on LSR-1 (with USMS) and MicroArm-II mounted on SRR



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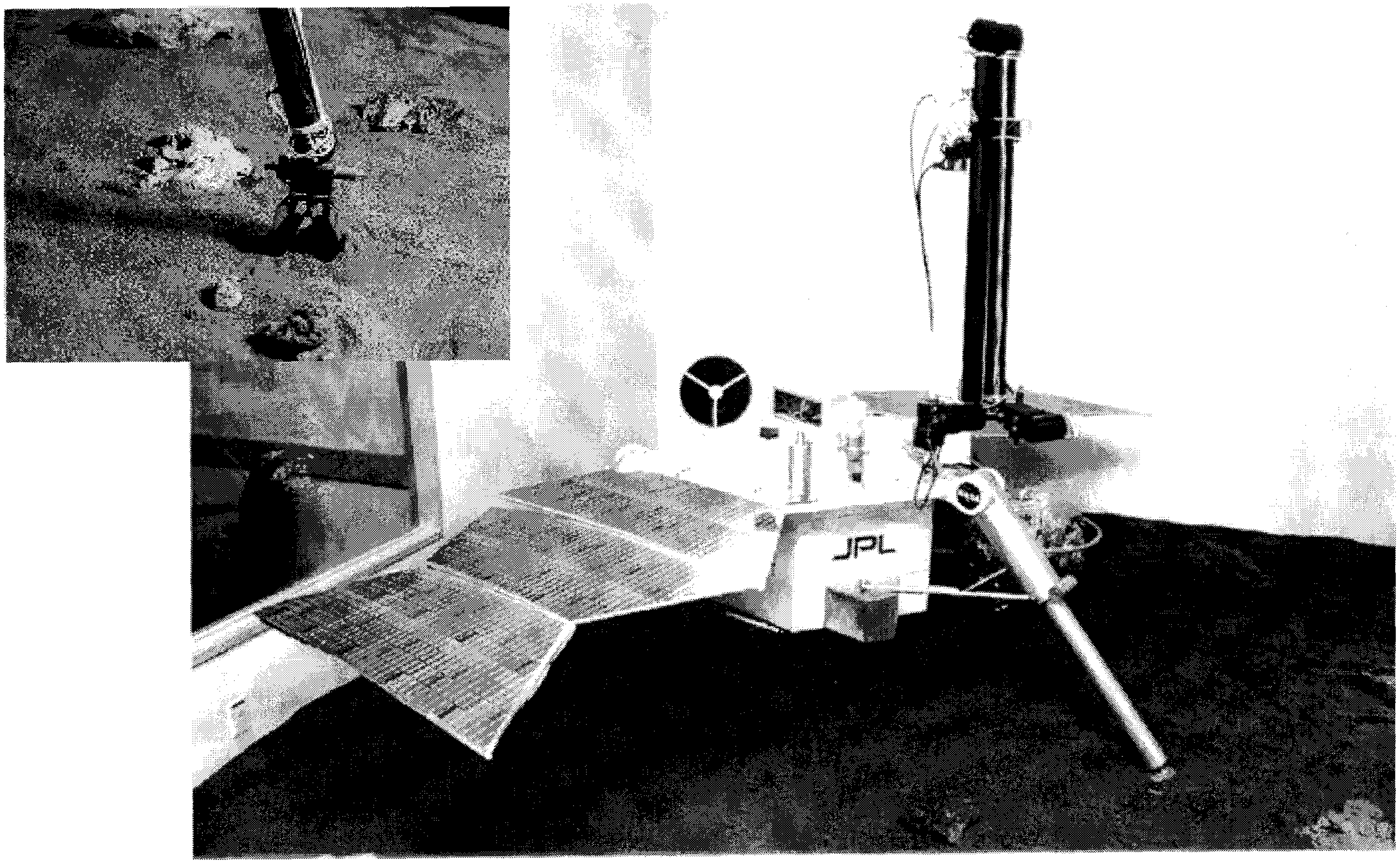
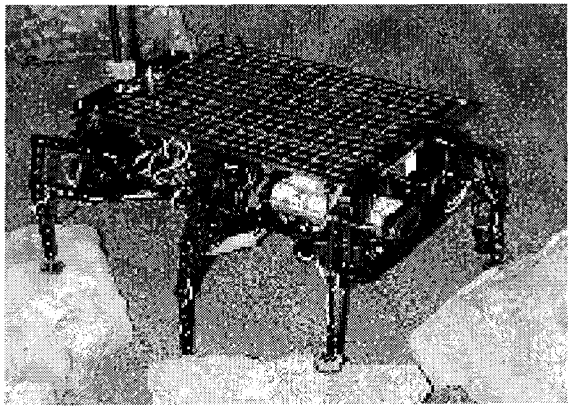
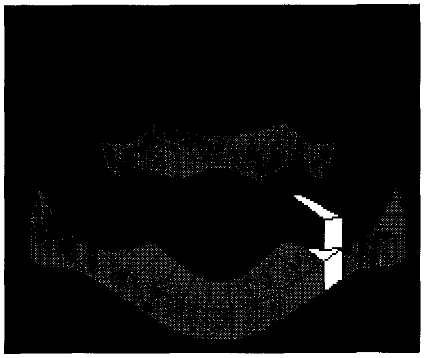
Mars Lander Dexterous Manipulator (MLDM) driven by USMs

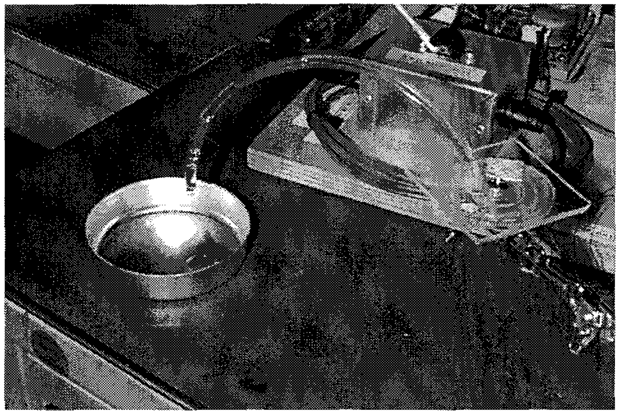


PLANETARY & COMMERICAL APPLICATION SPIN-OFFS



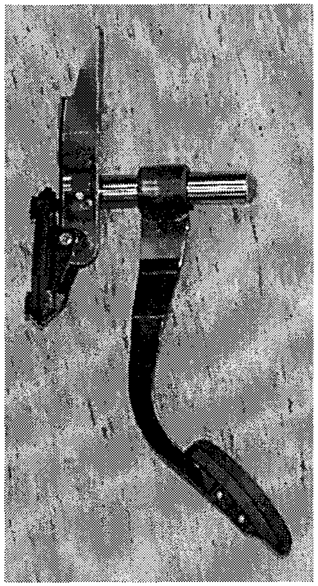
Hexabot - 6 legs robot



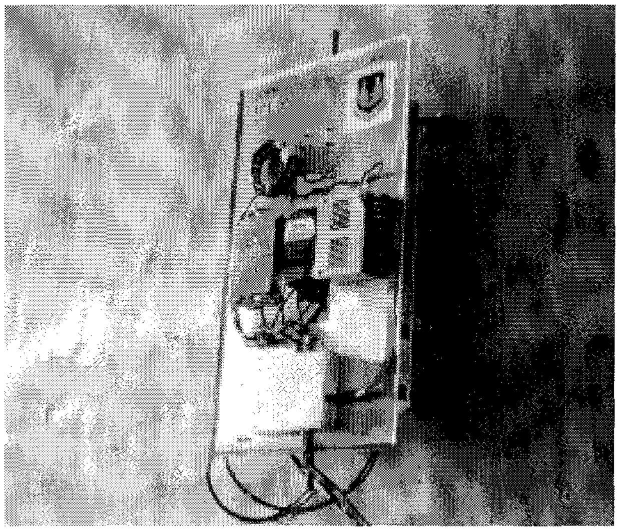


Piezopump – pump with no physically moving parts

Actuator for adjustable pedal of an automobile



Multifunctional Automated Crawling System (MACS)



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SUMMARY

- A hybrid model that addressed a complete ultrasonic motor as a system was developed.
  - The model allows using powerful commercial FE package to express the dynamic characteristics of the stator and the rotor in engineering practice.
  - An analog model couples the finite element models of the stator and rotor for the stator-interface layer-rotor system.
  - The model provides reasonably accurate results for CAD.

- Cryovac tests showed that the motors can stand with the temperature cycles on Mars and can be driven from room temperature down to -150 °C and 16-mTorr and still operate for at least several hundred hours.